CIRAN

Catalogue of emerging low-impact, low-visibility extraction methods

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Prepared by	Checked by	Verified by	Approved by
Jorge Carriedo	Marcelo Pereira José Mário C. Branco Mauro Lucarini	Ronald Ardvisson	Vitor Correia

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Executive Summary

The rising population, industrialization, and technological advancements are leading to a continuous increase in society's need for minerals. Simultaneously, finding new, easily exploitable high-grade ore deposits outcropping or near surface is becoming increasingly scarce and challenging.

Furthermore, unexploited regions containing mineral deposits for potential extraction frequently encompass locations with delicate environmental conditions, necessitating customized extraction techniques and practices.

At the core of a mining company's objectives is the identification of a mineral resource that can be exploited profitably, aligning with fundamental business principles. Within this overarching goal, a clear and robust trajectory emerges, underscored by a focus on two distinct disciplines as follows: firstly, there is a pronounced trend towards the digitalization of the sector, a trajectory in line with the contemporary era, incorporating terms such as "industry 4.0," signifying the industry's alignment with what some describe as the fourth industrial revolution (Originating in the mid-20th century, this revolution is characterized by a transformative shift from traditional business models to an economic paradigm grounded in information technologies); secondly, there is a strong commitment towards the adoption of sustainable mining practices, including responsible resource extraction, waste management, and remediation of mined areas, that can contribute to mitigating the environmental impact of mining towards a more sustainable economy and considerations on climate change.

A reasonable attempt taken by the mining industry for the adaption to this upcoming scenario comes through innovation and development of new technologies that could potentially minimize the environmental impact or even that could constitute a game changer to the mineral extraction sector. A successful approach in the field of low impact mining can unlock considerations for mining in sensitive areas perhaps not affordable by conventional methods.

The mine life cycle is a long-term process involving a wide range of disciplines at different stages, starting from a geoscientific approach in exploration towards the discovery of valuable resources suitable of being exploited. Once defined the economic resource, mining involves complex technical management of extensive workforce, high resources consumption, heavy machinery use, infrastructure construction and environmental impact restoration.

In this context, the scope for technological innovation is vast, encompassing a multidisciplinary spectrum that includes geology, geophysics, geochemistry, engineering, computing, safety, logistics, and more. Moreover, the range of innovation and emerging technologies spans from testing specific device prototypes to implementing entirely new extraction processes integrating multiple technologies.

Defining an emerging low-impact extraction method is not a straightforward task due to the multitude of interconnected variables that make it challenging to accurately estimate the impact using a single technology, sometimes without a proof of concept. In parallel, each mining project is unique, and the selection of appropriate methods will be tailored to its singularities. This document aims to offer a general overview of selected emerging technological trends in the mining industry, with a focus on potential minimization on the environmental impact, accompanied by a brief reflection on the primary technological challenges and opportunities.

The potential reduction in impact, although interconnected throughout the mine life cycle, is categorized into three distinct approaches. The first approach centres on overall mining optimization, a core focus that has seen substantial investment from the mining industry. Recent trends align with the industrial revolution and the adoption of information systems toward the ideal smart mining scenario. The comprehensive control of the mine life cycle, facilitated by robust communication systems, automation, real-time monitoring, and data analytics, is already diminishing the impact of mining while optimizing processes. In this line, the ongoing capabilities to cover multiple tasks remotely from Operating centres also increases the health and safety, with special impact on underground mining. This approach holds significant potential to bring about revolutionary changes in the industry over the next decades.

The second approach centres on emissions reduction, addressing a key impact that mines generate at both local and global scales. Any reduction in waste generation and resource consumption in conventional mining practices can profoundly impact how a mining operation affects its surroundings as widely indicated in the specific directive on the management of mining waste ("Directive 2006/21/EC on the Management of Waste from Extractive Industries and Amending Directive 2004/35/EC," 2006). Embracing renewable energies, decarbonization, and energy efficiency measures are essential for achieving sustainable development goals with a consideration for social and environmental factors.

The third approach focuses on minimizing the surface footprint associated with the presence of a mining operation in any geographic area, directly impacting surrounding communities or ecosystems. As an example, remediation processes to make the landscape have a use after mining is a critical aspect on footprint reduction. Open pit mining has a more significant impact in this regard compared to underground mining. Given the challenge of deeper potential resources, advancements in underground or alternative mining methods become an expected trajectory. Consequently, technological advances that enhance exploration capabilities for deeper resources indirectly contribute to reducing the overall surface footprint.

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1 Background and objectives

1.1 CIRAN project introduction

CIRAN will develop, test, and validate principles supporting systemic policy, , balancing environmental protection and societal needs for accessing critical raw materials (CRMs). This will be achieved through 1) streamlined permitting procedures in environmentally protected areas; 2) modern policies and social contract frameworks that reconcile the protection of environmentally sensitive areas and domestic sourcing of CRMs in the EU; and 3) the development of a community of practice in support of CIRAN goals and that will remain active after the project funding period.

CIRAN proposes a logical framework that justifies extraction based on a system-oriented assessment and the co-creation of knowledge (i.e., tested and validated by communities located in or nearby environmentally protected areas). It will create novel social contract models identifying rights, obligations, and responsibilities of governments (national/regional), communities and mine operators, capable of dealing with transformations and challenges due to climate change.

As a distinctive feature, CIRAN brings together 25 external experts on the environmental, political, social, economic, and technological factors that will shape the energy transition responses and the demand for CRMs. These experts, organised in four Expert Groups (EGs), will work with the Consortium, conveying insights on policymaking and implementation, economic drivers, technologies, mining, local governance, social capital, nature conservation and biodiversity. The EGs will actively engage in CIRAN through synergetic processes combining analysis and deliberation, and participation in project workshops and structured consultations (e.g., focus groups, foresight analysis).

The Consortium is geared to develop inclusive policy-making instruments that support the EU Green Deal and UN-led reforms to reach the climate commitments and sustainable development goals.

1.2 Work package 4 and objectives

This report is included on Task 4.1 at the CIRAN project, titled advanced extraction processes, technologies, and strategies of Work Package 4 (WP4) - Performance appraisals.

The main objectives of WP4 are:

- To define and explain the gaps between engineering design, technological capabilities, and environmental and societal performance.
- To gauge the use of mining technologies and processes over time and the long-term impacts of extractive activities in sensitive areas.
- To define factors to be considered in the assessment of CRMs extraction scenarios in environmentally protected areas.

The Task 4.1 has been focused on advanced extraction methods, including technologies, methods and processes used throughout the mine's life cycle, from the exploration phase to closure and remediation, also covering the MWEI-BREF on extractive waste management (Garbarino et al., 2018). The aim is to identify cutting edge and emerging mining technologies and strategies, providing a state-of-the-art picture of low-impact and low-visibility extraction options. This report is the result of this investigation which flag options and limitations for extraction methods that may be considered for use in environmentally protected areas.

2 Emerging technologies in the mining industry

Mining technology is the term used for the tools, equipment, methods, and systems used in the extraction of valuable minerals, metals, and other geological resources from the Earth's crust. This apparently simple definition includes an extensive and multidisciplinary range of items under the long-term evolving singularities on the sustainable and responsible management of Earth´s mineral resources.

This field has evolved significantly over the years, incorporating advanced technologies to improve health and safety, efficiency, and long-term environmental sustainability, reshaping the mining industry, since seems clear that mining companies that adopt these technologies are likely to gain a competitive edge and contribute to a more responsible and efficient mining sector.

At the complex business of a mine operation there is a wide range of research fields suitable to minimize the impacts along the entire mine life cycle and an overwhelming number of different processes to be considered in the operation. However nowadays, there is a clear bias on emerging technology trends driven by the ongoing industrial revolution, strongly focused on digitalization, data-based economies, and information systems (IS).

2.1 Criteria followed for the selection of low-impact, low visibility emerging technologies

The extraction of mineral resources is a complex industry that includes several stages along what is known as the mine-life cycle. Initial stages are defined by mineral exploration, aiming to find mineral resources suitable to be evaluated to be economically exploited. The last stage includes mine closure and remediation comprising the steps required to manage the area to minimize the environmental impact. Between these two end members of the mine life cycle, other stages include processes related to construction, extraction, treatment, disposal, and storage, all of them producing an inevitable impact in multiple ways. A reasonable approach is to discriminate which are the key environmental Impacts related with a mine operation to visualize which techniques offer advantages on minimizing them (Garbarino et al., 2021).

Low-impact, low-visibility mining techniques are approaches to resource extraction that aim to minimize the environmental footprint and limit the visual disruption caused by mining activities. These methods are particularly important when mining in ecologically sensitive areas or near communities were preserving the environment and maintaining a low profile are essential.

Due the wide spectrum of potential processes at different stages within a mining project, multiple multidisciplinary disciplines are involved such as geochemistry, engineering, computing, geophysics, or logistics among others, applicable to each of the mine life stages. Monitoring of this wide spectrum for a rigorous track of game changer emerging advances can be overwhelming, and each case requires dedicated research of specific improvements and technology readiness level or TRL (Héder, 2017), in many cases not public information.

On the other hand, the ambiguity of “emerging technology” or “low impact” concepts without clearly defined limits are a difficulty to constrain the classification, such as advances on specific components included in conventional techniques or a partial minimization of a high impact.

As a first approach, this report aims to provide a synthetic general overview of selected recent tendencies in terms of innovation for the mining industry with trends suitable to support more sustainable mining practices. The selection focuses on potential reduction of the environmental impact and the indirect potential to unlock mineral resources in sensitive areas. The compilation is not exhaustive neither evaluates the specific impact of each method but aims to provide an overview of the most recent technological trends capable to translate in mining impact reduction, in many cases combined with conventional methods.

The methodology comprised for the technology selection and report structure is based on feedback provided by CIRAN partners based on their expertise. After that a web search was performed for results on topics related to emerging low-impact, low visibility technologies in the mining industry. A synthesis text comes from scientific papers, mining companies reports, institutional reports, research centers and service providers sites and mining industry newsletters.

Both cited and consulted sources with references therein are summarized in the consulted bibliography section, as well as other topic related links included in the summary table associated with this report (Summary Table - Catalogue of emerging low-impact, low-visibility extraction methods) aiming to facilitate future reference towards more in-depth research as required.

2.2 Classification grouping of technologies in this catalogue

Based on the search performed results by consulting recent publications, public information and CIRAN partners contributions, a selection of technological trends has been grouped into three major groups in turn divided into three subtopics each: Mining optimization, Emissions reduction, and Footprint minimisation. Three letter acronyms are assigned to the different topics to favour the link with the summary table. A brief description of the rationale used for the main line of core technology is as follows:

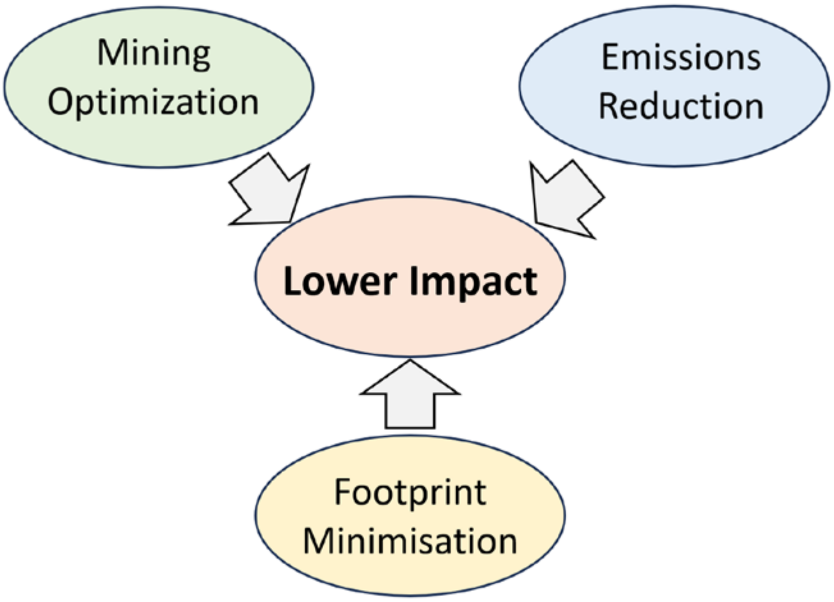


Figure 1 – Technological groups considered within this report as key drivers for a lower impact of a mining operation.

2.2.1 Mining optimization (MIO)

It refers to the process of optimising the health and safety, efficiency, profitability, and sustainability of mining operations through various techniques, technologies, and strategies. It involves among others the careful sustainable management of resources, reduction of waste, and improvement of overall productivity towards a more efficient operation. Some subcategories considered are the following:

1 Automation: includes the use of advanced technology and machinery to perform various tasks in the mining industry with minimal human intervention in the mine.

2 Energy Efficiency: definition of strategies towards the use of green energies and optimization workflows to minimize energy waste.

3 Ore Body Knowledge: related to deep knowledge strategies of the orebody to be mined supporting exploration and exploitation plans for a more efficient resource management.

2.2.2 Emissions reduction (EMR)

The term “emissions reduction” in this context pertains to initiatives and approaches focused on mitigating the environmental consequences of mining activities, with a specific emphasis on minimizing greenhouse gas emissions and preventing water contamination. Mining operations have the potential to release carbon dioxide (CO_2) and methane (CH_4) into the atmosphere during activities such as ore extraction, transportation, and processing. It is imperative to diminish these emissions to ensure the sustainability of the mining industry and its alignment with global initiatives to address climate change. At local scale, the emissions reduction in underground scenarios offers relevant improvements on health and safety. The three subcategories under consideration are as follows:

1 Decarbonisation: refers to the process of reducing CO_2 emissions to address climate change concerns and promote sustainability.

2 New Components & processes: advances on new materials consumed at the operation on specific actions favouring its performance and minimizing hazardous emissions.

3 Water treatment: water treatment options to meet regulatory standards, protect ecosystems, and ensure the responsible and sustainable use of water resources.

2.2.3 Footprint minimisation (FOM)

Minimizing the environmental footprint of mining is a critical goal for the mining industry as it seeks to reduce its impact on ecosystems, communities, and natural resources and requires a holistic approach that considers ecological, social, and economic factors. Sustainable mining practices aim to strike a balance between resource extraction and environmental stewardship, ensuring that mining activities are carried out responsibly and with minimal long-term impact. Three subcategories are highlighted:

1 Waste management: Methods to process waste for minimizing hazardous behaviours and being ecologically friendly.

2 Surface Impact: considerations to reduce the footprint of infrastructure and extraction activities in the surroundings of a mine operation.

3 Deeper Exploration: Advances towards non-invasive deeper exploration as the room for the discovery of new ore deposits.

2.3 Mining optimization technologies

Mining optimization technologies are a set of tools and approaches used in the mining industry to improve the efficiency, safety, and sustainability of mining operations. These technologies aim to enhance various aspects of mining, such as resource extraction, mineral processing, logistics, and environmental management. The last research trends for emerging technologies in the mining industry are strongly conditioned by the digitalization era that society is experiencing, aiming to achieve a more efficient, profitable, and sustainable operation (Young & Rogers, 2019). Computer based solutions, autonomous sensors and energy efficiency dominate the advances on the state of the art, since can be applicable to almost every stage within the mine life cycle. Tables 1, 2 and 3 include a summary of the described core technologies under each group in this catalogue, as well as bullet points on the nature of the potential impacts.

2.3.1 Autonomous monitoring of tailings dams and spoil dumps

Autonomous sensors can monitor the stability, safety, and environmental impact of tailings dams and spoil dumps in the mining industry, being an active field of research (*Autonomous Sensors Monitoring Tailings Dams and Spoil Dumps - Mining3*, 2023). By providing real-time data and early warning capabilities, these sensors contribute to risk mitigation and the overall sustainability of mining operations. Multiple parameters can be monitored simultaneously through application of different devices, suitable to be integrated through wireless communication systems for real time data analytics. Some novel and conventional devices suitable for autonomous monitoring include:

- Seismic Sensors: different sensors to monitor ground vibrations and seismic activity, providing information about the structural integrity of the dam. Some of the sensors include geophones to detect seismic waves or accelerometers to monitor ground vibrations.
- Geotechnical sensors: direct monitoring of dam deformation by widespread sensors tracking geotechnical parameters such as the slope or tilt of the ground (inclinometers), vertical settlements of the tailings dam (settlement gauges) or deformation in structural elements of the tailings dam (strain gauges).
- Groundwater pressure and flow: monitoring of groundwater behaviour around tailings is critical to ensure environmental safety. It can be achieved by the integration of multiple devices for different groundwater measurements such as pressure (piezometers), flow (velocity profilers), level (hydrostatic pressure sensors) or quality (conductivity meter).
- Differential Synthetic Aperture Radar Interferiometry (DInSAR): technology based on synthetic aperture radar (SAR) images taken at different times by satellites or aircraft (Othman et al., 2019). Image comparison through differential analysis allows the technology to detect changes in the earth´s surface.
- Persistent Scatterer Interferiometry (PSI): remote sensing technique based on Synthetic Aperture Radar (SAR) satellite images acquired over a specific area at different times (Crosetto et al., 2016). Tracking persistent scatterers that are stable and coherent, allowing to monitor ground deformation at millimetric scale.
- Time-lapse Electrical Resistivity Tomography (TL-ERT): Subsurface resistivity is controlled to certain extend by water content, an important aspect to control around tailings. This parameter can be monitored using Electrical Resistivity Tomography (ERT) and advances on time-lapse ERT to favour predictions (Dimech et al., 2023; Martínez-Pagán et al., 2021). A geo-resistivimeter for time-lapse analysis can be used as an autonomous system for real-time subsoil remote monitoring (Tresoldi et al., 2020). Cloud-based algorithms visualize resistivity changes, and an automatic control system triggers alerts for anomalies.

2.3.2 Big data management and artificial intelligence

Mining optimization through automation implies real time acquisition of a significant amount of data, increasing if new smart sensors are implemented in a modern interconnected operation. Also, the data management is moving towards a more cloud-based structure promoting effective communication systems for rapid data access (Qi, 2020). Technology is moving forward for assistance on both management and analysis of the data, fundamentally due research on Machine Learning (ML) and Artificial Intelligence (AI) as ongoing and future trends (D. Ali & Frimpong, 2020).

Artificial Intelligence (AI) is currently one of the most trending and transformative technologies across various industries. With its capacity to analyse vast datasets, make predictions, and perform tasks that traditionally required human intelligence, AI is reshaping the way we live and work. AI is increasingly being adopted in the mining industry to improve safety, efficiency, and productivity supporting the overall decision-making process as a key component in automation. It´s application has also the potential capability to apply predictive analytics for the operation performance in all aspects (Bag et al., 2022).

2.3.3 Communication systems

In the realm of mining operations, there exists a paramount need for reliable wireless communication systems that possess the adaptability to meet the continually evolving and demanding requirements intrinsic to the industry (Barbosa et al., 2016; Jang & Topal, 2020). The dynamic nature of mining activities necessitates communication solutions capable of scaling over time, seamlessly integrating with the robust demands of the digital transformation of the mining business. Furthermore, the escalating volume of data transmission within mining operations not only accentuates the significance of efficient communication systems but also introduces heightened challenges pertaining to cybersecurity. As the data flow intensifies, the strain on the network infrastructure becomes more pronounced, accentuating the importance of developing resilient wireless communication systems that can effectively handle the growing demands while concurrently addressing cybersecurity concerns.

Wireless technology has been a fast-growing technology in the communications sector being one of the largest carriers of data around the world. 5G communication technology has ultra-low latency and allows real time communication and data transfer required for the overall automation process and real time monitoring, enabling swift decision making and improved operational efficiency (Ma, 2020).

Communication systems using Compressed High Intensity Radar Pulse technology (CHIRP), can offer a wireless method complementing Global Position Systems (GPS) and Light Detection and Ranging (LiDAR) to exchange data towards positioning of assets including miners, mining equipment and vehicles (Dziengel, 2023). This long-range radio frequency technology has the potential to optimize operations by improving communication and coordination, reducing the risk of accidents. If combined with an IoT platform that sets the collected data into the context, CHIRP technology supports a robust real time location system (RTLS), very valuable for consideration at underground operations, helping to sustain reliable connection.

2.3.4 Core scanning technologies

The mineralization style and characteristics affect the entire mining operation, so optimization on the characterization of the ore deposit is a critical aspect. The extraction of the maximum value from the core by automatic core scan measurements of physic-chemical properties favours the ore body knowledge. This information can support exploration and targeted extraction, reducing waste generation. Some of the most used techniques for automatic core scanning include:

- Hyperspectral scanning: mineralogical identification based on short-wave infrared absorption features of key mineral specimens for classification (Tusa et al., 2019). It offers the option of develop mineralogical distribution maps of the scanned sample.
- X-ray Fluorescence (XRF): fast and non-destructive method to detect multi-elemental composition variations along the scanned drill core. The technique consists of irradiate the sample with x-rays and

measure the energy and intensity of the emitted fluorescent response to identify and quantify the elements in the sample (Klawitter et al., 2019).

- X-ray Computed Tomography (XCT): provides a three-dimensional image of the core scan providing insights into internal structures, porosity, or other properties (Luth et al., 2022). X-rays pass through the sample and detectors on the opposite site measure the intensity collecting X-ray images that are processed to reconstruct the internal structure of the core.

2.3.5 Drone technology (UAV)

The technology related to applications for Unmanned Aerial Vehicles (UAVs) has become increasingly important in the mining industry due to its ability to enhance safety, increase efficiency, and provide valuable data for various mining operations (Minh & Dung, 2023; S. Park & Choi, 2020). Drones are especially useful because they can capture data at a lower cost and higher accuracy than other methods and can be deployed in areas where humans are not allowed to enter. UAVs can fly without GPS, which is unavailable in most mining environments and challenging in sensitive areas. A wide range of possible applications cover the entire mine life-cycle from exploration to restoration, showing below a list of recent examples:

- Exploration data collection: new sensors are being adapted to UAVs aiming to reduce the cost of aerial geophysical and geochemical data collection in non-invasive exploration (Loots et al., 2022). Prototypes are continuously being developed to expand the applications for multidisciplinary data collection capabilities such as electromagnetics, metal ions migration or radiometric data among other conventional methods.
- Safety and Surveillance Enhancements: affordable real time aerial monitoring provides more control on the operation in terms of logistics or access, minimizing the risks and timing on specific response.
- Stockpile and construction monitoring: real time monitoring of infrastructure and stockpile status favours efficiency in terms of the derived workflows to be established in terms of feeding the plant or maintenance among others.
- Environmental monitoring: real time monitoring of the operation allows to quickly identify any possible environmental impact and implement corrective actions in appropriate time to mitigate the effects.
- Aerial seeding: reforestation using drones to precisely distribute seeds over large areas with challenging access and at a low cost. Equipped seeding devices can be programmed with GPS coordinates and flight paths for seed dispersal (X. Huang et al., 2020). Selected seeds are usually coated with a nutrient-rich material to enhance the chances of germination.

2.3.6 Integrated remote operating and monitoring centres (IROMCs)

The overall automation tendence of the mining industry is forcing the need of specific infrastructure for operations management through real time data acquisition, enhanced due shortage of skilled workforce at remote project sites and safety issues. The IROMC is an innovative way to maximize mine efficiency while reducing operational expenses and ensuring the highest HS&E standards at the workplace. The operators at IROMC have the capabilities to overview remotely integrated aspects of the operation in real time for quick decision-making processes (Storey, 2023). More and more capabilities are added to these centres as technology evolves, with some of the most relevant up to date as follows:

- Remote equipment control and predictive maintenance: Machinery equipped with sensors collecting real time data such as fuel levels or temperature while being operated from a centralized location through a robust connectivity. Data analytics through advanced algorithms identify patterns indicative of potential equipment failure.

- Safety monitoring and emergency response: Accurate control on workforce location and condition through wearable sensors, with effective detection and coordination for evacuation or other emergency situations.
- Environmental monitoring: Quick identification of a potential environmental issue through several sensors such as drones or water measurements devices allow and effective mitigation procedure due the linkage with the entire operation for the appropriate reaction.
- Resource optimization: integrated capabilities to apply optimization algorithms to allocate resources efficiently, considering factors such as demand, supply chain dynamics, energy consumption or appropriate workforce deployment based on real-time needs.

2.3.7 Internet of things (IoT)

Internet of Things plays a critical role towards full automation of a mine operation, since involve connecting physical objects, machinery, and equipment to the internet and collecting and analysing data from these devices (Molaei et al., 2020).

Considering the overall automation, big data, and predictive maintenance, a wide range exists of ways in which IoT could support sustainable mining improvements such as achieving cost and productivity optimization, improving safety measures, and developing their artificial intelligence needs.

The key challenge comes by the surge in diverse static and mobile IoT devices, varying in speed and bandwidth, combined with a growing demand for high data rates, intensifying network complexity. In response, the forthcoming sixth generation (6G) communication technology aims to lay the groundwork for future network deployment needs (Pattnaik et al., 2022).

2.3.8 Ore body knowledge (OBK)

Ore body knowledge refers to the comprehensive understanding of the geological, mineralogical, and geophysical characteristics of a mineral deposit or ore body. This knowledge is crucial for mining companies and geologists as it forms the foundation for making informed decisions about the feasibility, economics, and operational planning of a mining project. Expenditure on appropriate data collection for proper understanding of the orebody to be mined is the most effective path to avoid mistakes and maximize extraction activities. Digitalization of historical data with every technology providing geoscientific good quality and standardize data collection will feed the OBK implementation. Some critical aspects to consider on the application are related with spatial resolution of this information:

- Geological modelling: geological modelling has evolved through new 3D software capabilities for both explicit and implicit modelling, capable to produce fast interpretations of the subsurface geology (Guo et al., 2020).
- Data integration and analytics: the 3D geological models can be populated with other multidisciplinary datasets using 3D grids (Ugalde et al., 2019). This allows the integration of multiple measured or generated variables for each cell in the ore deposit context.
- Digital Twins: The efficiency on the use of a virtual replica of a physical mining asset as a digital counterpart that mimics the real-world entity in both its physical characteristics and behaviour. The goal is to create a comprehensive and dynamic model that enables monitoring, analysis, and optimization of mining operations.

2.3.9 Ore pretreatment for grinding

Since comminution represents around 50-70 % of the energy consumption at a mine operation, efforts to minimize this effect have been explored through pretreatment of ore (Adewuyi et al., 2020). Promising results have been obtained at lab scale on different technologies such as chemical additives, thermal treatment, microwave treatment, ultrasonic treatment, or electrical disintegration. Unfortunately, at industrial scale, these technologies have not been yet properly implemented and more research is required. Some of the last emerging technologies include:

- Water-jet comminution: high pressure water jets used to cut, erode or fragment a wide range of materials without a relevant environmental impact. Water-jet cutting also facilitates the work of tunnel-boring machines.
- Bio-milling: an environmentally friendly technique that involves the use of microorganisms to enhance the extraction of valuable metals from ores, such as oxidizing or dissolving insoluble compounds.
- Radio frequency heating: the use of electromagnetic waves at radio frequencies to heat and modify targeted subsurface materials can promote the release of minerals from the orebody.
- Shock wave pretreatment: Controlled shock waves are generated by specialized devices, adapting the wave parameters for the weakening of the selected material by the generation of microfractures and stress.

2.3.10 Pulsed fast thermal neutron activation (PFTNA)

Pulsed fast and thermal neutron activation (PFTNA) technology rapidly delivers highly representative elemental analyses for process control in real time (Reichardt et al., 2022). PFTNA offers the mining industry a non-destructive and rapid method for analysing the elemental composition of geological samples. This information is crucial for making informed decisions at all stages of mining operations, from exploration and resource assessment to production and environmental management. As examples, this technology can measure nearly the complete flow on a passing belt conveyor and provide a composite analysis in minutes, or allows the analysis of soil, sediment, and water samples to detect any contamination or alterations in elemental composition caused by mining activities.

2.3.11 Remote sensing

The development of remote sensors is exploding with an exponential increase of devices available for multiple data collection purposes following the digitalization and automation trends (Duarte et al., 2022; Havisto et al., 2021). Remote sensing is also playing a crucial role in exploration, with more applications on aircraft, UAV or satellite data collection for target generation.

This satellite monitoring has also applicability during the closure stages through monitoring of ecosystem behaviour after restoration and quantify the environmental impacts (Hui et al., 2021; Islam et al., 2020; Song et al., 2020)

Light Detection and Ranging (LiDAR) is a laser light analysis method extensively used for creating Digital Elevation Models (DEM). This technique also favours the monitoring of changes at the surface linked with mining activities (Maxwell et al., 2014).Another technological trend is the application of extremely low-frequency magnetic signals to carry out underground ranging measurements and data transmissions while drilling (*Remote Borehole Sensors - Mining3*, 2023). This involves the research and development of a system that can wirelessly measure underground temperature and pressure in geothermal regions. Wireless underground sensor systems offer the advantage of eliminating underground sensor cables (no breakage issues) and surface receiver equipment at damage safe locations, away from the hole collar.

2.3.12 Robotics

Robotics has emerged as a promising solution to improve safety and efficiency in mining operations in several aspects (D. Ali et al., 2023), overall distinguished by application to drilling, haulage and inspection.

- Grade control sampling: Drilling rigs focused on grade control can be automated to certain extent in terms of sampling programming without the need of human supervision.
- Autonomous trucks or railways: replacement of haulage vehicles by a fleet of autonomous machinery that optimize logistics and avoids the human interaction. In combination with AI, these machines execute tasks with high efficiency.
- Inspection robots: monitoring at dangerous or sensitive areas becomes derisked using inspection robots or drones (Zimroz et al., 2018). Unstable underground zones for example can be inspected through a robot collecting information about the status and supporting decisions on how to proceed prior human deployment.
- Real time data collection: Autonomous devices need to be monitored and are providing real time data continuously. By the addition of sensors on this machinery, they significantly contribute to the overall automation process and processes control.

2.3.13 Sensor based ore sorting technology

Intelligent ore sorting technology is a cutting-edge innovation in the mining industry that uses various sensors and advanced algorithms to efficiently separate valuable ore from waste material (Luo et al., 2022; Munteanu et al., 2020; Robben & Wotruba, 2019). There are several sensor technologies being applied at real cases, usually combined with high-speed conveyor systems, or even installed in mining machinery like front loaders. Sorting decisions are made in real time, ensuring that valuable material is efficiently separated. The most common sensors being used can include:

- X-Ray Transmission (XRT): sensors are used to measure the intensity of transmitted X-rays through the ore particles and differentiate between minerals based on their X-ray absorption properties (Robben et al., 2020). Based on the analysis, the system in a conveyor triggers an ejection mechanism to divert or separate particles into different streams in terms of purity.
- X-Ray Fluorescence (XRF): like XRT, in this case the sensors focus on measuring the x-ray fluorescence from the irradiated samples, and each spectrum is analysed through algorithms to determine the elemental composition of the ore (Cetin et al., 2023).
- Near Infrared Radiation (NIR): the material is irradiated with near-infrared radiation, interacting with the minerals that have a unique spectral signature. NIR sensors measure the reflectance or absorbance spectrum of the particles and used to determine the chemical composition of the ore.
- Laser Induced Breakdown Spectroscopy (LIBS): this technique is based on the generation of plasma through the interaction of a high energy laser with the sample. The plasma emits spectral lines as the electrons recombine with the ionized atoms. The emitted light is analysed to determine the elemental composition of the material.

- Magnetic Resonance (MR): The sensors apply strong magnetic fields and radiofrequency pulses to the material and certain atomic nuclei absorb and re-emit electromagnetic signals that are analysed to determine the elemental and molecular composition of the ore particles.

Table 1 – Mining Optimization Technologies and positive expected impacts.

Emerging technological trend	Expected impact
Artificial Intelligence (AI)	Automation Mining efficiency Cost reduction Environmental impact assessment
Autonomous monitoring of tailings dams and spoil dumps	Reduce human presence from hazardous areas. Active and continuous monitoring allowing frequent safety audits. Improved tailings dams and spoil dump designs and maintenance. Anticipation of mitigation needs.
Big data management and analytics	Integrated holistic control. Mining optimization through automation. Predictive analytics.
Communication systems	Lower energy consumption. Long-range positioning. Resistance to radio frequency interference.
Core scanning technologies	3D rock and ore characterization. Mining efficiency, feed for the automation general process. Non-destructive, consistent, and relatively rapid rock property analysis. High resolution core imaging. Standardization and digitalization of geological features.
Drone technology	Reduced Environmental Footprint by optimizing the operation and reducing physical inspections. Accurate Environmental Monitoring by provision of real-time data, aiding in early detection or mitigation of environmental issues. Improved Remediation monitoring vegetation growth and ecosystem restoration. Monitor water management and keep erosion under control. Assessment of areas with complex accessibility.

Emerging technological trend	Expected impact
Integrated Remote Operating and Monitoring centres (IROMCs)	Mining efficiency Energy consumption Optimization Integrated monitoring and quick response Reduced human presence
Internet of Things (IoT)	Increase mining efficiency through automation. Cost reduction. Data integration for effective holistic monitoring. Predictive maintenance. Reduction on emissions and pollution.
Ore Body Knowledge (OBK)	Favor decision making process. Maximize extraction process efficiency. Optimization of exploitation plans. Minimization of environmental impact.
Ore pretreatment for grinding	Comminution energy reduction.
Pulsed Fast Thermal Neutron Activation (PFTNA)	Quick determination of material chemistry enabling high speed automatic process control. Non-destructive technique. Highly representative data. Environmental and operator safety. Cost-savings from rapid process control and no sample preparation.
Remote sensing	Mining efficiency. Risk reduction. Real time monitoring. Fast response and decision-making support.
Robotics	Minimize human exposure to hazardous environments and tasks. Real time data collection supporting decision making process, including areas with challenging access. Enhancement of task performance and resource management. Detection and avoidance of obstacles for autonomous operations.
Sensor based ore sorting technology	Improved resource recovery. Reduction in energy consumption. Grinding cost reduction. Minimize tailings production.

2.4 Emmisions reduction technologies

2.4.1 Alternative explosives

Blasting for rock fragmentation is a common practice in the mining industry, where the most used explosives are the Ammonium Nitrate and Fuel Oil (ANFO). Most conventional explosives use an ammonium nitrate base, what the inherited risk of generating harmful pollution of dust and nitrogen oxide fumes, impacting mining sites and adjacent atmospheric environment (Oluwoye et al., 2017). Abatement technologies had focus efforts on reformulation of explosives, replacing the nitrogen component by hydrogen peroxide as the main oxidising agent. Explosives based on hydrogen peroxide emulsion are already at commercial stage, whereas alternative formulae continue being focus of research.

2.4.2 Bioleaching

Bioleaching is a microbial process that harnesses the metabolic activities of naturally occurring or genetically modified microorganisms to extract valuable metals from ores and concentrates (Kaksonen et al., 2020; Kržanović et al., 2019; Yin et al., 2021), including applications on tailings. The process involves oxygen supply to create aerobic conditions and favour microbial activity that oxidizes sulphide minerals by acid production. The acid produced helps to release the target metal ions into solution, that can be recovered by purification techniques like precipitation, solvent extraction, or electrowinning. Promising future improvements of this technology come from:

- Biolectrochemical systems (BES): the design of BES influences the metal extraction process from microorganisms by incorporating customized electrodes (Brar et al., 2021), acting as electron donors or acceptors that provide additional control and efficiency of the process.
- OMIC sciences: Advances on the global analysis of biological information covered by the omic sciences to understand the structure, function, and interactions of biological systems (Jerez, 2017). It includes several disciplines based on the field of research such as DNA (Genomics), RNA, (Transcriptomics) or proteins (Proteomics) among others.

2.4.3 Carbon capture, storage, and utilization (CCSU)

Mining operations can be significant sources of greenhouse gas emissions, primarily due to the use of heavy machinery, transportation, and energy consumption. Implementing carbon dioxide (CO_2) capture technologies (Osman et al., 2021) in the mining industry can help reduce the environmental footprint of these operations and contribute to global efforts to combat climate change. The fields for application in mining involve CO_2 capture directly from emissions sources such as diesel generators or processing plants. mineral carbonation involves that CO_2 emissions are captured and reacted with alkaline materials such as mine tailings or waste rocks to form stable carbonates (Bobicki et al., 2012). The main limitation comes from the favourable geological features available, more suitable at ore deposits linked with mafic rocks.

A relevant effort in research is still needed for CO_2 utilization as a sustainable process in the mining industry towards implementation of appropriate technology. These trends point to CO_2 utilization for making new products such as building materials or low carbon fuels. The most relevant technological advances for carbon storage applied to mining industry come from synergies between large mining companies and demonstrated results in other industries or case studies.

2.4.4 Electric furnace smelters

The processing of ores and minerals for the extraction of commodities through pyrometallurgy involves high temperatures and energy consumption, with associated emissions. There is a general trend away from pyrometallurgy towards hydrometallurgy but still some challenges to consider and in general remains to be a combined process.

Regarding CO_2 emissions, as an alternative to traditional fossil fuel-based furnaces, electric furnaces tend to be more energy efficient and cleaner. These furnaces use electricity to generate heat, which is then used to melt and refine metals and other materials extracted from mining, commonly related for example with steel production. Below a couple of examples on electric furnaces:

- Electric Smelting furnace (ESF): design studies for pilot scale furnaces (BHP -Hatch, see annex table for reference) for producing steel from iron ore, replacing the use of coal by electricity and hydrogen, with potential significative reductions of CO2 emissions.
- Electric Arc furnace (EAF): a high-power electric current is supplied to create an electric arc between the electrodes and the charged materials in the furnace. The arc generates high temperatures creating a pool of molten material.

2.4.5 Electric Vehicles (EVs)

As part of the electromobility trend, electric vehicles (EVs) have gained increasing attention and adoption in the mining industry due to their potential to reduce operational costs, improve safety, and reduce environmental impact (Sánchez & Hartlieb, 2020). These vehicles have been implemented on haul trucks, electric loaders, electric drills, and several underground vehicles, with a direct impact at local scale by improving the air quality at underground environments, where hybrid diesel-electric equipment have delivered successful tests.

The adoption of electric vehicles in mining is expected to continue to grow, with advancements in battery technology and infrastructure development supporting the overall automation and digitalization trends complementing the electrification efforts in the industry.

2.4.6 Geotextile separators

Geotextiles are films made of synthetic material whose main role is to create a physical barrier between the ground and other materials with permeable movement of water or gases. Widely used in the mining industry (Post & Maubeuge, 2018), the opportunity for impact a mine operation comes from exploring different ways to be applied. Technological advances focus on expand applications such as for conventional dewatering and efficient water management using geotextile tubes, the reclamation of abandoned mines through meandrically arranged geotextiles (Broda et al., 2020) or even attempts considered to recover valuable raw materials from acid mine drainage (Lira Santos et al., 2023; Nasiadka, 2022).

2.4.7 Hydrogen vehicles – Green hydrogen

The widespread Diesel-powered haul trucks in the mining industry are responsible for up to 80% of a mine's emissions. This type of vehicles in underground mining operations represent a health risk due the great quantity of pollutants generated. The application of alternative energy like hydrogen could solve these issues towards a more sustainable operation but not exempt of risks and limitations (Guerra et al., 2020). Hydrogen cells can be also adapted to other mining equipment or infrastructure combined with a sustainable hydrogen production plan.

2.4.8 Renewable energy operations

Mining is an energy intensive industry (Pouresmaieli et al., 2023), with recent tendences over mining projects turning into renewable energies to feed the operation consumption, reducing emissions and non-renewable energy consumption (Igogo et al., 2020). However, the ratio of using renewable energy versus non-renewable energy at the mine operation is still very low. Solar and wind energy seem to be the technologies with more chances to be implemented in the mining industry (Strazzabosco et al., 2022) but has other challenges like the climatologic limitations or the land requirements for infrastructure (Zharan & Bongaerts, 2017). The most common renewable energy technologies for commercial use include the following:

- Biomass: refers to the energy derived from recently living organisms and it can be replenished through natural processes. The main pathways to produce energy from biomass involve direct combustion to produce heat or electricity, or the application of biological and thermal processes to produce biofuel (eg. ethanol) or biogas (eg. methane).
- Solar: this technology takes advantage of sunlight to generate electricity or heat. Photovoltaic solar power utilizes solar cells to convert sunlight into electricity through the photovoltaic effect. Solar thermal technology uses collectors that absorb sunlight to heat a fluid for residential or industrial purposes.
- Wind: Wind turbines have blades that capture kinetic energy of the wind. The blades are connected to a rotor that turns a generator, converting mechanical energy into electrical energy.
- Geothermal: Heat from earth´s subsurface is transferred to surface through conduction and convection, that can be used to generate electricity by driving turbines from high temperature steam. There is a direct use on heating infrastructure for domestic or industrial purposes.
- Green Hydrogen: green hydrogen is produced through electrolysis of water powered by renewable energy sources. Hydrogen fuel cells apply an electrochemical reaction to generate electricity by the production of water from hydrogen and oxygen, as the only byproduct.

2.4.9 Sonic drilling

This innovative green mining drilling technology uses high-frequency mechanical vibrations to break and remove subsurface materials (Qian et al., 2021), making it distinct from conventional drilling methods. It can be used for several purposes during the mine life cycle like mineral exploration, environmental drilling, waste management or geotechnical investigations. A key advantage of this technique is the reduction or avoidance of drilling fluids, reducing water consumption, environmental impact, and safety at the workplace, with also advances done on research focused on combining this technology with online real time analysis (Orberger et al., 2019). The main limitation comes from maximum depths drilling capacity, lower when compared with conventional drilling.

Table 2 – Emissions Reduction Technologies and expected positive impacts.

Emerging technological trends	Expected impact
Alternative explosives	Less environmental impact through elimination of nitrates and blasting decarbonisation Sustainable and renewable fuels in explosive formulations Reduced public risk
Bioleaching	Minimize the production of hazardous waste materials Avoidance of sulphur dioxide emissions Energy efficiency Remediation of mine tailings Potential for useful resides
Carbon capture, storage and utilisation (CCSU)	Reduction of CO2 emissions Utilisation of CO2
Electric furnace smelters	Lower greenhouse gas emissions and air pollutants Energy efficiency Higher precision and control of temperature
Electric vehicles (EVs)	Operating costs reduction Energy efficiency Lower environmental impact through less emissions Lower noise and vibration
Geotextile separators	Emissions to soil and groundwater Emissions to surface water Dewatering applications for efficient resource recovery
Hydrogen vehicles - green hydrogen	No harmful emissions. Quick refuelling times. Energy efficiency Decarbonisation
Renewable energy operations	Decarbonisation Decrease greenhouse gases and other harmful emissions Reduce transport of diesel fuel Cost reduction

Emerging technological trends	Expected impact
Sonic drilling	Minimal waste Reduced water usage Versatile from soils to hard rock Faster than conventional drilling

2.5 Footprint minimisation technologies

2.5.1 3D printing

One of the significant advantages of 3D printing is its ability to produce customized parts and equipment on-demand, including prototyping and design optimization. This capability is extremely useful in mining for the need of replacement parts at remote locations quickly, optimizing the operation performance and reducing the need of extra land for spare parts storage (Bishwal, 2019). This technology can be also applied at exploration stages through the generation of physical geological models or tools required for collection and analysis. Another demonstrated use is the capability of print diamond composites using an additive manufacturing process called stereolithography, that can be used for cutting, drilling, or grinding tasks at the operation.

Parallel research has been focused on the use of industrial waste materials such as mine tailings for 3D printing of sustainable concrete (Dey et al., 2022), as a potential field of advance for a more sustainable economy.

2.5.2 Bioremediation

Bioremediation utilizes microorganisms to break down or detoxify contaminants, with an extensive literature on methods applicable to a wide range of polluted scenarios (Shah, 2020), including mining waste (Newsome & Falagán, 2021). Sulphate-reducing bacteria for example can help reduce the acidity and remove heavy metals from acid mine drainage, making it less harmful to the environment. In the case of alkaline waste, these techniques can be also used to reduce conductivity and salinity.

One of the most relevant contaminations linked with the mining industry is probably the one linked with heavy metals and metalloids, hazardous for human life. In this line, research is ongoing with bioremediation potential of microorganisms like bacteria, fungus or algae among others (Jeyakumar et al., 2023).. Is critical in the selection of the technique to be used a proper understanding of the behaviour and functions of microbial communities, what recently is being explored with the support of OMIC sciences (Sharma et al., 2022).

The application of these technologies can contribute on minimizing the environmental footprint of the mine waste after closure, and in addition, exists the potential combination with biomining techniques, aiming for the recovery of valuable elements during the remediation process (Hoque & Fritscher, 2019).

2.5.3 Brine mining technologies

Desalination plants are more and more common in the mining industry as a source of water for the operation. Recent advances in research are evaluating the optimization of the desalinization process through the generation of mineral rich concentrates as a subproduct from the water desalinization process (Mavukkandy et al., 2019; Sharkh et al., 2022).

Linked with brine mining, Direct Lithium Extraction (DLE) is a set of emerging technologies and processes designed to extract lithium from various sources (Grant, 2020), including brine deposits and geothermal brines. Its application depends on the specific lithium source, the economic viability and the potential short- and long-term environmental impacts (Vera et al., 2023). Even with limitations, is considered a potential key development in ensuring a stable supply of lithium for the growing demand in battery technologies, electric vehicles, and renewable energy storage (Stringfellow & Dobson, 2021).

From a wide spectrum of methods, some of the most transformative technologies in this topic include:

- Nanofiltration (NF): a membrane-based separation technology with selective permeability allowing water molecules to pass through while rejecting a significant portion of dissolved salts.
- Microbial desalination cell (MDC): bioelectrochemical system that relays on the metabolic activities of microorganisms capable to generate electricity as they metabolize organic matter.
- Electrodialysis (ED): electrochemical process for removing ions from water. ED uses an electric field to transport ions through ion-exchange membranes, separating solutions with different ion concentrations.
- Ion-exchange resins: polymeric structure resins that can attract and replace ions in the resin with ions in the solution. Depending on the resin´s functional groups, it can selectively remove specific ions enabling customize extraction setup options.
- Solvent extraction: used in other metallurgical sectors, involves the extraction of a substance from a liquid mixture with a solvent, relying on the differential solubility of components in two immiscible phases. After the mixture, the solvent phase containing the extracted component is separated from the feed phase.

2.5.4 Dust control

Dust control in mining is essential for maintaining a safe working environment (Liu et al., 2021), protecting the health and safety of workers and surrounding communities. Minimizing the environmental impact of both underground and surface mining operations must consider dust since it can be generated from various sources, including blasting, drilling, crushing, loading, and transportation of materials. Dust has critical impact on underground scenarios (Paluchamy et al., 2021) and ventilation innovation is an active field of research (Tukkaraja & Sasmito, 2023).

Implementing effective dust control techniques is crucial to mitigate these sources of dust emissions, specially at sensitive areas due the presence of communities or protected habitats. Water based methods are the most common dust suppressant used but has challenges in terms of sustainability and effectiveness. Relevant research focuses on the design of effective and biodegradable binders. Some dust control methods include:

- Dust suppression spraying technology: water spraying generates mist with droplets that can capture dust particles in the air (Peng et al., 2019). Spraying devices can be customized to optimize droplet needs, with atomization generating fine sprays at very low flow rates being reinforced.

- Chemical binders: the function of a binder is to agglomerate fine particles and create a cohesive layer that prevents dust from becoming airborne (Zhang et al., 2020). The chosen type must be defined by specific environmental conditions such as temperature, humidity, or wind patterns.
- Foam dust suppression: surfactant-based solutions are used to generate foams applicable to surfaces and blankets the material providing a longer-lasting dust control effect.
- Shotcrete Dust Control Technology: the spraying of concrete with biding agents to generate a solid layer that reduces the potential for dust generation and improve stability of soil and rock surfaces.
- Bio-chemical dust suppressants: consist of the use of biological or organic substances to supress dust (Wu et al., 2020). For example, microbes and enzymes can break down organic materials in the soil improving its structure and reducing the generation of dust. Biopolymers produced by fermentation using bacteria can generate substances with binding properties.
- Wind fence barriers: On specific situations, physical barriers are effective methods to reduce wind speed and minimize dust generation, that can be combined with other techniques impact minimization.

2.5.5 Enhanced rock support

As underground mines delve deeper in pursuit of additional ore deposits, the gravitational and tectonic pressures pose a significant challenge when it comes to securing tunnels. Traditional methods of tunnel support lose their effectiveness as depth and stress increases, leading to a substantial demand for enhanced reinforcement (Cai et al., 2022). Hence, the focus shifts towards investigating and crafting innovative high-energy dissipation systems that can endure the immense pressures of deep mining by boosting load-bearing capabilities. A couple of tested examples include:

- Concrete filled steel tubular support (CSTS): this reinforcement consists of a continuous steel tube that is shaped to match the cross-sectional profile of the roadway and is then filled with concrete (W. P. Huang et al., 2018). Compared with conventional U-type support, this method has the potential to increase both bearing capacity and structural stability.
- Grouting reinforcement technology: Grouting technology is based on the use of a dense liquid, usually including a mixed of water, cement, and sand, that is projected to fill the voids of fractured rock domains, increasing tunnel stability and deformation for a safer work environment (Fangtian et al., 2016).

2.5.6 In situ recovery

In Situ Recovery (ISR) or in Situ Leaching (ISL) is a low-impact method of metal recovery that involves the dissolving of a metal value from ore in situ into a fluid and pumping this fluid to the surface for processing (Sinclair & Thompson, 2015).

Electrokinetic in situ leaching (EK-ISL) induces the migration of lixiviants using an electric field, with promising results on extraction of gold and metals (Martens et al., 2018, 2021; Ortega-Tong et al., 2023), enhancing the importance of the host rock reactivity with the selected lixiviant. Research to support this technique is strongly focused on the chemistry of lixiviants enhancing recoveries through environmentally friendly components.

ISL could be a game changer in mining industry procedures, but not suitable for every mineralization style and no projects producing right now excluding Uranium examples due it´s solubility. Florence Copper Project in Arizona is probably the most advanced metallic deposit aiming to apply this technology, obtaining successful tests on high grade copper cathode production capabilities in 2019 (*Taseko Mines / Florence Copper*, n.d.).

2.5.7 Mine backfilling

Backfilling is a technique used to refill underground mine voids created by extracting valuable minerals, maximizing resources utilization, and minimizing the environmental impact (Li et al., 2021; Xue et al., 2023). The main purpose is to achieve geotechnical stability for pillar exploitation while using dumps or tailings as backfilling materials to reduce waste disposal. The choice and treatment depends on the project's requirements and the specific engineering and environmental considerations. Proper compaction and drainage are essential to ensure the long-term stability and safety of backfilled areas. There are four main types of backfill based on the type of material, including paste backfill, hydraulic sand fill, cemented fill and dry rock fill.

Cemented paste backfilling (CPB) with reuse of tailings material is extensively used in the mining industry (Qi & Fourie, 2019) and has been the focus of recent research to maximize its utilisation into deeper conditions of high stress and temperature. Research is being focused on integrated CPB designs supported by machine learning methods and new paste materials beyond the Portland cement, as the most used. Examples of new materials include:

- Alkali-activated pozzolanic materials: The paste mixture includes materials like ash, slag or other byproducts that are rich in reactive silica and alumina, which are activated by alkali solutions to form a solid and durable backfill (Cihangir et al., 2015).
- Phosphogypsum backfill material: phosphogypsum is a byproduct from phosphate rock mining and the processing of fertilizers that can be treated to be reused as a mixture for the paste backfilling (Zhou et al., 2022).It provides additional structural support while reusing the aggregate in a sustainable approach.
- Superplasticizer: these materials are usually added to the filling paste admixture for improvement on flowability, achieving a more efficient gap filling process.

2.5.8 Novel geophysical methods

Improvements on geophysical exploration technologies are transforming the way in which mineral resources are discovered and evaluated. The advances include an improved identification of subsurface targets with higher resolution and accuracy data, applicable to challenging environments higher depth penetration and capabilities for covering large areas in less time and at a lower cost (Dentith et al., 2018; Haritha, 2023; Nevalainen et al., 2021). The main techniques explored include Electromagnetic methods such as Airborne electromagnetics or transient electromagnetics; Seismic methods such as 3D seismic imaging or Multi-component Seismic imaging; Gravity and magnetic methods such as Airborne gravity and magnetic surveys, full tensor gradiometer or superconducting gravimeters; Ground penetrating radar and Borehole geophysics. Most techniques are conventional, but there have been dramatic improvements in the interpretation methods due more powerful computers, machine learning assistance and 3D visualization capabilities.

Even if great technology improvements have been accomplished on the existing technologies, there are scarce emerging new technologies. The room or opportunity for improved deeper geophysical exploration comes from the integration of multiple methods to characterize resources potential from different sources. Joint geophysical inversions are considered as part of the data treatment innovation.

2.5.9 Passivation against Acid Mine Drainage (AMD) generation

In mining, metals and metal-containing compounds can leach into the environment, posing environmental and human health risks, being a research front to minimize them. Passivation focuses on treating mining waste with passivating agents that promote the formation of a stable, protective oxide layer on the surfaces of metal-containing waste materials (I. Park et al., 2019).

There is an extensive literature on the subject, with numerous probed methods applicable to prevent AMD generation (Garbarino et al., 2018; Yang et al., 2023). Recent studies point to the combination of different conventional technologies for appropriate prevention (Mosai et al., 2024), rather than relying on a single new technology. The rationale is because in general, a single method focuses in one type of AMD, so tailored combined solutions for the specific project based on its requirements is probably the most effective approach.

Microencapsulation (Chen et al., 2021), as a novel way of passivation, aims to encapsulate toxic materials within a protective shell, making them less prone to leaching, and supporting the design of waste containment structures, such as liners for tailings ponds or landfills, to prevent the migration of contaminants into groundwater or nearby ecosystems.

2.5.10 Phytomining - Agromining

Phytomining recently referred as Agromining, is a method of extracting valuable metals, such as nickel, copper, and gold, from soil or mine tailings using specially selected hyperaccumulating plants (Morel et al., 2021; Nkrumah et al., 2019; Sheoran et al., 2009). These plants are capable of absorbing and concentrating metal ions from the soil into their biomass. Once the plants have absorbed enough metals, they are harvested and incinerated to recover the valuable metals from their ash.

2.5.11 Removal of dissolved substances

It's essential to strike a balance between effective removal of dissolved substances and minimizing the generation of additional waste or environmental harm in the process (Wang et al., 2021). Sustainable mining practices often focus on efficient water treatment to ensure that the water discharged from mining operations meets environmental standards (Yuan et al., 2022). Another research field is to recover valuable elements in the treatment process.

One approach is the use of semi-permeable membranes removing particles based on their size and properties. In other cases, it involves the addition of chemicals that react with the dissolved minerals causing them to precipitate. Some remarkable methods include:

- Forward Osmosis: application of a semi-permeable membrane for separation of water from dissolved solutes (A. Ali et al., 2021). Is a low energy method since water flux is driven by osmotic pressure, allowing the solvent to move across the membrane from the lower to the higher solute concentration, retaining the dissolved solutes on the other side.
- Electrocoagulation: destabilization of dissolved elements through the application of an electrical current over submerged metal plates acting as electrodes, releasing metal ions and favouring the formation of insoluble precipitates (Mamelkina et al., 2017).
- Use of microbial mats or algae: cyanobacteria are photosynthetic organisms capable to survive at extreme conditions of pH and salinity, as well as high concentrations of metals and contaminants. These organisms are photoautotrophs and can saturate the water in oxygen during daylight and

consume it at night, what allows them to sequester a wide range of metals through alternating, reduction, or oxidation among others.

- Continuous stirred tank reactor (CSTRs): are conformed by deposits for mine drainage input through and entry point and a flow under continuous agitation and mixing with specific reactants for water treatment, exiting the reaction product through the opposite exit point.

2.5.12 Tunnel boring machines (TBM)

A Tunnel Boring Machine (TBM) is a specialized piece of equipment used in underground tunnelling and excavation projects. TBMs are self-contained machines designed to excavate tunnels, bore through rock, soil, or other geological formations, and simultaneously install tunnel linings or support structures. This technology is an alternative to the drill and blast techniques, potentially improving safety and advance rates, however, a proper understanding of the geological setting is required to evaluate its applicability (Zheng et al., 2016). Innovation in cutterhead design is one of the main research fields in TBM.

Table 3 – Footprint Minimization Technologies and expected positive impacts.

Emerging technological trend	Expected impact
3D printing	Reduction of land usage and surface footprint Optimized supply chain with less energy consumption
Bioremediation	Reduction of mine waste toxicity
Brine Mining technologies	Alternative source of elements. Reduction of brine disposal to the sea. Subproduct from seawater desalinization Reduction of hard rock mining for lithium
Dust control	Increased worker safety due improved air quality Reduced environmental impact Water saving Soil stability Reduced brake distance
Enhanced rock support	Safe Human operability at greater depths Deeper production

Emerging technological trend	Expected impact
In situ recovery	Small surface footprint Reduced tailings generation Low-carbon emissions Low energy and low capital-intensity mine. Reduced water usage through recycling
Mine Backfilling	Land subsidence prevention Transformation of resources to reserves Reduction of tailings disposal. Increased water recovery
Novel geophysical methods	Non-invasive targeting tools with low environmental impact Application for areas with challenging accessibility Screening for deeper resources with potential to be mined underground with lower surface impact
Passivation against acid mine drainage (AMD) generation	Reduction of mine waste toxicity
Phytomining/Agromining	Environmental remediation Low environmental impact Resource recycling Sustainability
Removal of dissolved substances	Decontamination of potential harmful water
Tunnel boring machines (TBM)	Dust and noise reduction Mine efficiency Enhanced safety and remote control Integrated tunnel support mechanisms Lower emissions

3 Limitations and options for the implementation of selected low impact technologies on environmentally protected areas.

The mining sector plays a pivotal role in providing society with essential raw materials crucial for social development and for the manufacturing of a myriad of products that constitute our daily surroundings.

Mining in environmentally protected areas presents unique challenges due to the need to minimize ecological disturbance and comply with stringent environmental regulations locally. These challenges are enhanced due to respect on climate change mitigation strategies.

The use of low-impact and low-visibility technologies can help to cope mining exploration and environmentally protected areas. This catalogue presents a set of emerging techniques or methods capable of minimizing negative impacts on the environment at different stages of the mine's life cycle. However, it should be noted that several emerging techniques still have limitations in their applicability on a large scale, in cost competitiveness, and on its own development.

It will always be necessary to adjust the choice of cutting-edge, low-impact technologies to be used in mining exploration to respond to the real values to be preserved and protected in environmentally sensitive areas. Tailored solutions for the specific needs of each mining site are a critical key decision step that should be based on a deep understanding of the project singularities and potential impacts to be minimized.

3.1 Limitations and challenges

3.1.1 Technology maturity

When considering the implementation of cutting-edge technologies, there is always a risk related to the adoption of unproven technology, usually related to the state of development and maturation of the emerging technique. The evolution of the emerging technologies is conditioned by the three major challenges of any project: being performance, schedule, and budget. The three of them are conditioned by the priority of the specific research field according to ongoing strategies of the investing stakeholders.

The Technology Readiness Level (TRL), initially formulated by NASA to gauge technology maturity and employed as a tool for technology push strategies, has been extended as an assessment tool for public sector innovation. However, evaluating readiness levels is a challenging endeavour, particularly for technologies with intricate processes. This complexity introduces the risk of inaccurately assessing readiness levels and the associated development priority, resulting in delays and a shortfall in the implementation plan. In addition, novel techniques and technologies with potential for impact reduction are not accepted by regulators as not being sufficiently proven and forecloses options for improvement.

Drilling, an unavoidable facet of the mining industry vital for resource definition and subsurface information collection, remains a costly and technologically stagnant process. Despite incremental advancements, drilling necessitates the surface deployment of heavy machinery to investigate anomalies identified during exploration, even when non-invasive methods were initially employed and considered low impact procedures. The minimum requirement for surface drilling becomes imperative to amass foundational knowledge and unlock resource definition scenarios beneath the surface by establishing the necessary access infrastructure. However, environmental regulations, particularly in certain areas, may impose constraints on this minimum surface drilling, potentially impeding subsequent low-impact operations unless specific regulatory approvals are obtained.

3.1.2 High and risky investment

The infusion of cutting-edge technologies into mining operations necessitates a substantial upfront investment, initially envisioned during the exploration stage to identify a high-quality resource. However, as mining operations progress into pre-feasibility and economic scenarios, certain technological applications may encounter limitations, potentially confined to protracted operations and high production rates capable of substantiating the initial investment outlay. The lifespan of a mine remains contingent on a multitude of factors, encompassing resource size, grade, affordable production rates, and exploration potential—a complex estimation further compounded at greater depths.

Preserving a low-visibility footprint emerges as a critical imperative in protected areas to safeguard their innate beauty and ecological equilibrium. The visual impact of mining operations, especially in open-pit scenarios, poses a formidable challenge, often compelling mining projects to shift towards subterranean scenarios, a preference that extends even to shallow resource exploration. This strategic transition bears significant economic ramifications, manifesting in escalated operational costs and diminished resource recovery, thereby heightening the threshold for the requisite ore deposit quality during the exploration stage.

Is relevant to note however that under a raising economic and societal pressure to obtain critical materials prices more likely will go up, so return on investment will potentially become more secure.

3.1.3 Applicability and scalability challenges

Not every technology can be applied at every project due the wide range of combined geological and non-geological settings conditioning the singularities of each site. This is a critical aspect to be considered in the mining industry since in contrast with other sectors, the mine can´t be placed at any geographic location. The area of potential impact is directly related to the presence of the economic resource and being distance to mill a critical economic factor for a mining project viability. Mining companies tend to use a preliminary geographic approach in terms of where to explore, but once an economic resource is discovered, every effort focuses on how to adapt strategies for the project viability. This is also applicable to technology applications, then in most cases needs to be customized and adapted for the specific needs of the project.

As an example of limitation due the geological setting, the potential use of complex and novel exploitation processes such as in situ leaching, will be strongly conditioned by suitable geological settings where nature provides the required ingredients for its evaluation (e.g., leachable ore, sufficient permeability, proper fracturing control, etc), in addition to the common grade and tonnage considerations.

Access restrictions to protected areas can stem from a multitude of factors, with biodiversity protection emerging as a predominant concern. These regions serve as habitats for rare or endangered species and delicate ecosystems, underscoring the imperative need for meticulous consideration of activities preceding the implementation of any technological interventions. An illustrative example lies in non-invasive drone-based exploration surveys, which, despite aiming to avoid direct harm, may inadvertently disturb bird species, highlighting the necessity to exercise caution and circumvent areas adjacent to nesting sites.

In terms of renewable energy implementation strategies, some could be limited by climatological conditions, such as enough solar radiation or wind for turbines, or directly no room for infrastructure placement due topography, protection standards, communities, or visual impact among others.

Another challenge for scalability of certain technologies is the associated need for skilled personnel to manage and maintain the technology, which could represent a challenging recruiting process due the very specific expertise required and addressing potential job displacement concerns in the workforce. In parallel, a robust training programme is essential to be planned in conjunction with any novel technology implementation to maximize the benefits while mitigating potential risks. In other words, the introduction of new technologies requires a careful management of the lead-times, as supporting infrastructure and training facilities need to be developed with foresight.

3.1.4 Digitalization emphasis

The digitalization trend is everywhere, and while the inclination towards real-time monitoring portends heightened mining efficiency through a more robust integrated control system, it necessitates a harmonized approach with the simultaneous development of innovative physical mitigation techniques. However, the ongoing data collection stage reveals a dual challenge, wherein the fervour for data acquisition must be counterbalanced with the concurrent development of new technologies designed to efficiently minimize environmental impact. The nascent stage of this technological evolution denotes a limitation, with the strong minimization of environmental impact yet to be fully realized.

The prevailing trend towards digitalization and information management entails grappling with exponentially expanding datasets, giving rise to challenges in maintaining data quality and security. The calibration and standardization of real-time data assume pivotal roles in ensuring that decisions are grounded in dependable facts. Despite concerted efforts to ensure data security and privacy, the data generated by emerging technologies may confront complexities, especially in remote and sensitive areas.

3.2 Options and strategies

3.2.1 Real time holistic monitoring

In the dynamic landscape of technological advancements, recent progress has ushered in a new era where cutting-edge sensing technologies provide a substantial advantage. Beyond the confines of merely maximizing operational efficiency and profitability, these advanced sensors play a pivotal role in the intricate task of assessing and monitoring the environment, particularly in areas of ecological sensitivity. Their deployment serves as the bedrock for minimizing environmental impacts and ensuring unwavering regulatory compliance, marking a paradigm shift in responsible resource utilization.

A tangible manifestation of this technological prowess is exemplified in the groundbreaking initiation of preliminary drone-based non-invasive data collection. This innovation stands as a cornerstone in the comprehensive undertaking of Environmental Impact Assessments (EIA). Beyond the conventional approaches, this method not only facilitates the identification of potential impacts but also plays a crucial role in formulating effective mitigation strategies. Furthermore, it fosters a heightened level of engagement with relevant regulatory bodies and stakeholders, ensuring a transparent and collaborative assessment process from initiation to conclusion.

The overall automation and data driven environment of industry 4.0 with the overwhelming advances in this line is the future towards an operation strictly controlled what will minimize the environmental impact of the operation. Of course, just control is not enough since once could monitor forever without taking actions to mitigate an issue without any impact, however information is critical to understand reality. With the overall increased knowledge quality, is expected that new technologies will ramp up by the needs to resolve specific monitored events, but this impact perhaps still to come.

3.2.2 Green protocols for energy consumption

A Mining operation involves an intense energy consumption activity due the conventional systematic processes utilized to extract the valuable materials from the waste rock. The commitment to embracing alternative energy sources for mining machinery, steering away from fossil fuels, represents a gold standard in environmentally protected areas. This commitment is not merely a nod to technological advancement but a testament to a holistic solution brimming with myriad benefits. The transition to a non-fossil fuel fleet transcends its impact beyond supporting the large-scale adoption of renewable energy and contributes substantially to the overarching goal of decarbonization. On a local scale, especially within environmentally sensitive regions, this transition becomes a catalyst for enhancing air quality and reducing noise pollution. The ripple effect of these changes is the minimization of disturbance to wildlife and nearby communities, embodying a holistic and sustainable approach to mining practices that extends beyond mere resource extraction.

An overall reduction on the amount of energy consumed is also crucial strategy with promising future, since in addition of the valuable environmental implications, it has an economic impact on the mine operation performance and return, conforming a winner key strategy to be prioritized in the extraction process. A combination of investment in modern efficient machinery, the overall automation for optimization and energy waste minimization (e.g., haulage), as well as technologies like ore body knowledge and ore sorting to reduce over-extraction, are promising trends to continue developing.

3.2.3 Zero mining waste paradigm

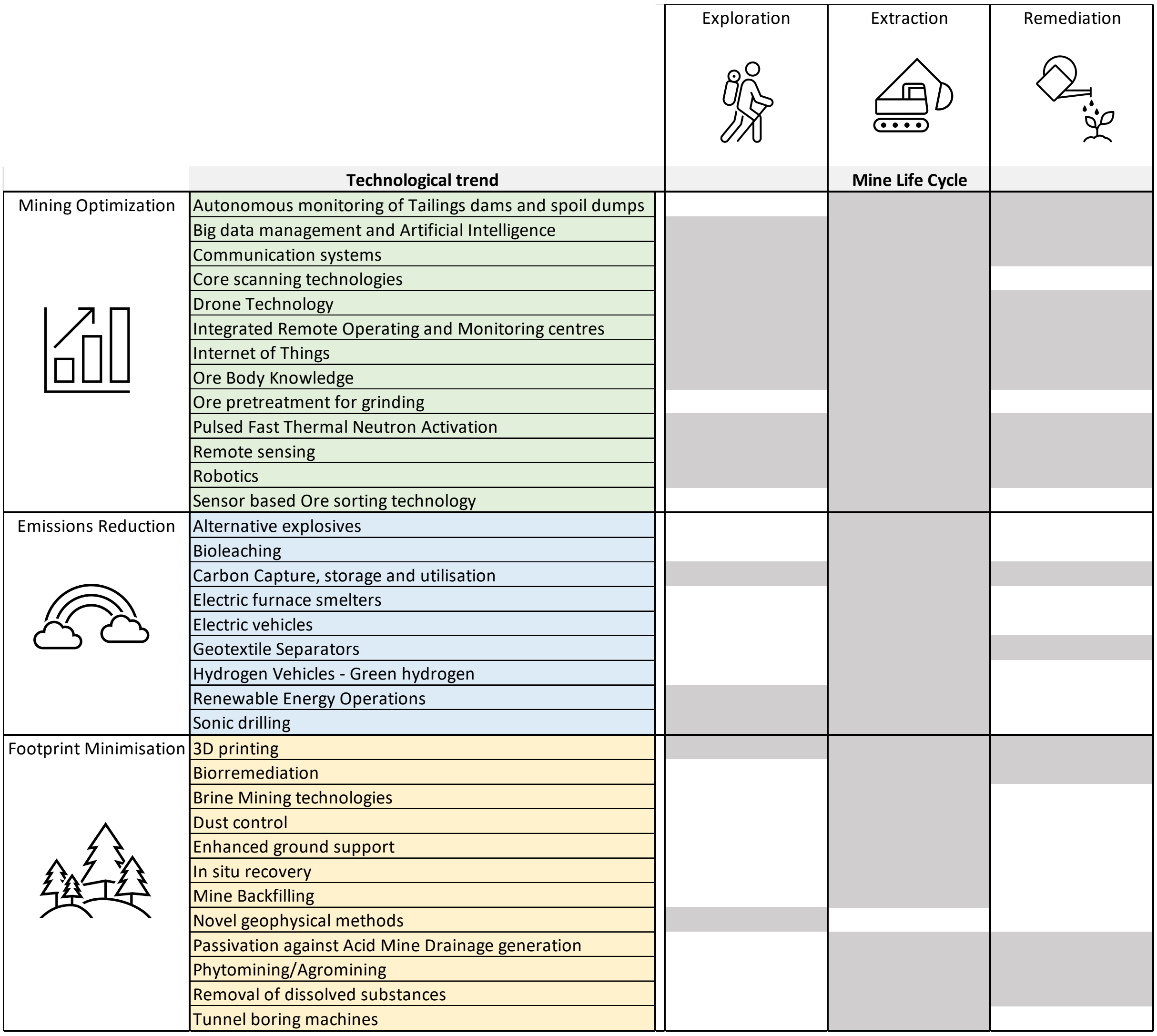
Yet, the multifaceted nature of mining operations reveals an inextricable facet—the generation of waste as non-economic material during ore extraction. The challenge lies not only in the environmental repercussions of waste generation but also in its economic implications, with factors like the stripping ratio in conventional mining playing a pivotal role. Optimizing the stripping ratio becomes a strategic imperative, influencing not only environmental concerns related to generated waste but also economic considerations such as costly earth movement. In addressing this challenge, technological advancements emerge as powerful tools, with increased ore body knowledge, digital twinning for robust exploitation plans, and real-time ore sorting technology standing out as effective strategies for substantial waste reduction. Additionally, responsible waste management practices, such as paste backfilling or treatment for industrial purposes, align with the principles of the circular economy, exerting a profound environmental impact by minimizing disposal.

The aspirational goal of moving towards a nearly invisible near-zero waste mining scenario represents the pinnacle of the ideal technological paradigm, albeit a formidable challenge not possible to achieve in most cases. Several technological trends align with this aspirational approach, introducing revolutionary methods for extracting valuable materials with the ultimate purpose of meeting society's needs. The potential success on application of alternative extraction methods such as in situ leaching or phytomining, and the incorporation of circular economy approaches, exemplified by tailings recycling plans during production, could collectively contribute to a reduction in the surface footprint of mining operations.

An indirect yet impactful environmental benefit stems from the overarching trend towards automation and the establishment of remote operation centres through innovative monitoring and control systems, located away from the mine environment. This trend not only facilitates a reduction in on-site personnel but also results in a diminished physical presence in environmentally sensitive areas, concurrently reducing the footprint with less extensive surface infrastructure and logistical activity.

4 Conclusions

Minimizing the ecological footprint of the mining industry is essential for balancing the need for resource extraction with environmental and community considerations. The demand of critical materials is raising and needs to be supplied through sustainable mining practices while minimizing the negative effects on the environment and surrounding communities. Focused technology advances play a key role on the achievement of this goal along the path (Figure 2).



	Technological trend	Exploration	Extraction	Remediation
			Mine Life Cycle	
Mining Optimization	Autonomous monitoring of Tailings dams and spoil dumps		▨	▨
	Big data management and Artificial Intelligence	▨	▨	▨
	Communication systems	▨	▨	▨
	Core scanning technologies	▨	▨	
	Drone Technology	▨	▨	▨
	Integrated Remote Operating and Monitoring centres	▨	▨	▨
	Internet of Things	▨	▨	▨
	Ore Body Knowledge	▨	▨	▨
	Ore pretreatment for grinding		▨	
	Pulsed Fast Thermal Neutron Activation	▨	▨	▨
	Remote sensing	▨	▨	▨
	Robotics	▨	▨	▨
	Sensor based Ore sorting technology		▨	
Emissions Reduction	Alternative explosives		▨	
	Bioleaching		▨	
	Carbon Capture, storage and utilisation	▨	▨	▨
	Electric furnace smelters		▨	
	Electric vehicles		▨	
	Geotextile Separators		▨	▨
	Hydrogen Vehicles - Green hydrogen		▨	
	Renewable Energy Operations	▨	▨	
	Sonic drilling	▨	▨	
Footprint Minimisation	3D printing	▨	▨	▨
	Biorremediation		▨	▨
	Brine Mining technologies		▨	
	Dust control		▨	
	Enhanced ground support		▨	
	In situ recovery		▨	
	Mine Backfilling		▨	
	Novel geophysical methods	▨		
	Passivation against Acid Mine Drainage generation		▨	▨
	Phytomining/Agromining		▨	▨
	Removal of dissolved substances		▨	▨
	Tunnel boring machines		▨	

Figure 2 – Summary of covered technological trends linked with a simplified mine life cycle. Grey zones indicate applicability potential along the cycle.

The primary challenge for innovation in the mining industry initiates during the exploration phase, focusing on the transformative and efficient utilization of technology to discover high-quality ore deposits viable for exploitation. This marks the initial step before contemplating technological approaches for low-impact extraction methods. To prioritize future advancements, particular attention should be given to tailored data acquisition as the cornerstone of exploration activities. As an example, progress in the combined application of UAVs, innovative geophysical methods, and remote sensors is imperative to optimize exploration target definition at areas with difficult accessibility.

Drilling stands as a pivotal industrial action in the mining sector, providing essential subsurface information crucial for business development along the mine life-cycle. Although drilling technology has seen limited evolution in areas such as partial automation and process efficiency, its reliance on heavy machinery deployment remains a challenge, especially with the trend toward deep drilling in exploration. Even if considered a low impact process, this technological constraint lacks a clear short-term solution and must be considered, particularly in sensitive areas, as an initial minimum disturbance necessary for strategic impact minimization throughout the extraction process.

Considering the significance of drilling as the primary information source for potential ore deposits, investing in technological advances to enhance data acquired from drill cores, such as core scanning technologies, is a justified minor investment atop overall drilling cost. Improving digital and standard datasets from drill samples is essential for enhancing integrated 3D models, optimizing ore body knowledge, and ensuring the reliability of digital twins—a fundamental prerequisite for the entire extraction process.

Automation processes play a pivotal role in the extraction stage, emerging as a clear winner in terms of ongoing technological advances and potential impact on the mining sector. Holistic control of smart mining processes yields benefits ranging from efficiency to impact minimization. The surplus of new data collected becomes the foundation for defining additional technologies, developed, tested, and implemented through customization for the unique specifics of each mining project. Ongoing enhancements in remote sensing diversity and communication systems, supported by AI, are likely to drive future technological advancements, addressing potential issues through continuous learning.

In future scenarios, the endeavour to extract natural resources in environmentally protected areas may find itself restricted to subterranean operations, seeking to minimize surface impact and curtail waste generation by exploiting “hidden” ore deposits. However, this strategic paradigm shift is not without its drawbacks, as it introduces heightened operational costs and grapples with challenges in production rates, thereby limiting economic viability. The quest for equilibrium between environmental preservation and economic imperatives continues to be a pivotal challenge in the realm of sustainable mining practices, with an ever-evolving knowledge base demanding ongoing research effort.

Lastly, it is crucial to focus on novel extraction methods beyond conventional mining activities, such as in situ leaching or brine mining technologies. These types of alternative exploitation methods could be a game changer and redefine research strategies and technological innovation trends in the mining industry, already accelerating.

The development of new methods comes from the need to satisfy a demand of procedures to unlock the viable exploitation of orebodies at singular settings. The tailored solutions tend to come from an adapted combination of methods for each specific situation. The continuous learning enhanced by the raising data acquisition and monitoring more likely will provide valuable approaches for more sustainable mining practices.

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Annexe 1 – Summary table of selected emerging low Impact low visibility extraction methods (in alphabetical order)

Tecnological trend	CODE	Mine Life stage	Application examples	Some topic related links
3D printing	FOM	All stages	Boliden - Sandvik agreement - Sweden	https://blog.dixonvalve.com/technology-trends-mining-industry https://www.zeal3dprinting.com.au/services/3d-printing-for-mining-industry/ https://theintelligentminer.com/2021/06/17/five-applications-for-3d-printing-in-mining/ https://www.geplus.co.uk/news/mining-companies-to-trial-3d-printing-for-machine-parts-21-04-2022/
Alternative explosives	EMR	Extraction	Tests at Pinjarra Hills blast chamber - Australia Commercial Hypex Bio Explosives Technology AB - Sweden	https://www.mining3.com/research/alternative-explosives/ https://hypexbio.com/about-hypex-bio/ https://www.nouryon.com/products/hydrogen-peroxide/hydrogen-peroxide-based-emulsion-explosive-/ https://im-mining.com/2023/08/08/mining3s-alternative-explosives-project-finding-the-right-formula/
Autonomous monitoring of tailings dams and spoil dumps	MIO	Disposal	Germano mining complex (Brazil) Prototype delivered by mining 3 project to partner ACARP Mosul Dam	https://www.mining3.com/research/autonomous-sensors-tailings/
Big data management and Artificial Intelligence	MIO	All stages	Escondida (Chile)	https://miningmagazine.com.au/unearthing-the-full-potential-of-big-data-in-mining/ https://www.mining-technology.com/data-insights/leading-mining-companies-in-the-artificial-intelligence-theme/?cf-view https://www.digitalsupercluster.ca/projects/earth-xray-for-low-impact-mining/
Bioleaching	EMR	Extraction	Zijinshan Copper Mine - China Mianhuakeng Uranium Mine - China	https://www.angloamerican.com/futuresmart/stories/our-industry/mining-explained/mining-terms-explained-a-to-z/bioleaching-definition-and-process#:~:text=Bioleaching%20(or%20biomining)%20is%20a,such%20as%20bacteria%20or%20archaea. https://cordis.europa.eu/article/id/443153-bioleaching-eco-mining-benefits-agricultural-sustainability

Tecnological trend	CODE	Mine Life stage	Application examples	Some topic related links
Biorremediation	FOM	Extraction/Closure	Gilt Edge Mine, S.D. (EEUU) Golden Sunlight Mine, Whitehall, Montana Force Crag (UK) Rampgill (UK)	https://projects.itrcweb.org/miningwaste-guidance/to_passivation.htm https://theintelligentminer.com/2020/01/08/mining-and-carbon-negative-bioremediation/
Brine mining technologies	EMR	Extraction	UK startup Cornish Lithium Fénix project - Argentina Lanke Lithium Project - China EuGeli project - France	https://www.startus-insights.com/innovators-guide/discover-8-top-sustainable-mining-solutions/ https://www.brgm.fr/en/current-project/eugeli-lithium-extraction-geothermal-brines-europe
Carbon capture, storage and utilisation (CCSU)	EMR	All stages	BHP-HBIS pilot - China Test at Gahcho Kué mine - Canada	https://www.bhp.com/news/media-centre/releases/2023/03/bhp-signs-carbon-capture-and-utilisation-pilot-agreement-with-chinas-hbis-group https://news.utexas.edu/2023/03/24/new-mining-technology-uses-co2-as-tool-to-access-critical-minerals/ https://arpa-e.energy.gov/technologies/programs/miner https://www.riotinto.com/en/news/releases/2021/rio-tinto-and-carbfix-partner-for-carbon-capture-and-storage https://www.1pointfive.com/dac-technology https://www.canadianminingjournal.com/featured-article/using-tailings-to-get-to-net-zero/
Communication systems	MIO	All stages	NA	https://www.inpixon.com/technology/standards/chirp-spread-spectrum https://www.scientific.net/AMR.1079-1080.787 https://www.industrial-innovation.com/top-seven-innovations-in-connected-mining-mass-improvements-in-yield-economics-and-safety/
Core scanning technologies	MIO	Exploration/ Extraction	Antakori (Peru) George Fisher mine (Australia) Lovisa Deposit (Sweden)	https://minalyze.com/ https://corescan.com.au/wp-content/uploads/2020/11/SEEING-THE-UNSEEABLE-ANTAKORI-PROJECT-PERU.pdf https://corescan.com.au/services/hyperspectral-mineralogy/ https://www.geotek.co.uk/products/mscl-s/

Tecnological trend	CODE	Mine Life stage	Application examples	Some topic related links
Drone technology	MIO	All stages	Jellinbah Group Gold Fields Ghana Ltd. Juomasuo, Kuusamo - Finland Heinävesi and Tuusniemi - Finland Rompas, Ylitornio - Finland	https://blog.dixonvalve.com/technology-trends-mining-industry https://wingtra.com/drones-for-mining/ https://www.flyability.com/mine-drone https://www.propelleraero.com/blog/how-drone-technology-contributes-to-esg-in-mining/ https://dronesurveyservices.com/benefits-of-drones-in-mining/
Dust control	EMR	All stages	Vitoria Plant - Brazil Big Stone Road - Canada Codelco Norte - Chile Pilbara Mine - Australia South Flank Mine Project (BHP) - Australia Koodaideri Project (Rio Tinto) - Australia	https://www.siethomgroup.com/wp-content/uploads/2023/06/Wind-Fence-Effectiveness-case-study1.pdf?_gl=1*bhrqlb*_up*MQ..&gclid=CjwKCAjw_uGmBhBREiwAeOfsd26WsPrv8myjAmWYmtTv0URqXA1VhABLC_hcJ4h7ly9frA7MYwef2hoC6aIQAvD_BwE https://globalroadtechnology.com/grts-featured-product-smart-dosing-units/ https://bind-x.com/ https://news.dustaside.com/3-innovative-dust-control-measures-underground-mines https://abcdust.net/dust-suppression/ https://www.enviro-mist.com.au/technology/
Electric furnace smelters	EMR	Smelting	BHP-Hatch pilot	https://www.bhp.com/news/media-centre/releases/2023/03/bhp-and-hatch-commence-design-study-for-an-electric-smelting-furnace-pilot
Electric vehicles	EMR	Extraction	Minas Gerais (Brazil) - Vale Gudai-Darri iron ore mine (WA) - BHP Skanska's Vikan Kross quarry, near Gothenburg, Sweden	https://chargeoninnovation.com/ https://www.vale.com/w/vale-is-the-first-mining-company-to-test-100-electric-72-ton-trucks/-/categories/64919 https://thedriven.io/2022/11/24/caterpillar-tests-massive-battery-electric-mining-truck-destined-for-australian-mine/ https://www.e-mj.com/features/market-traction-grows-for-electric-mining-vehicles/
Enhanced ground support	FOM	Extraction	El Teniente mine - Chile Huafeng coal mine - China	https://www.mining3.com/research/ground-support-mining-great-depth/
Geotextile separators	EMR	Disposal	Application in most operations	https://link.springer.com/article/10.1007/s40891-023-00433-2 https://www.earthshields.com/geotextile-application-in-mines/ https://www.researchgate.net/publication/367126779_Dewatering_of_Mine_Tailing_Slurries_Using_Geotextile_Tube_Case_Histories https://researchrepository.wvu.edu/etd/11276/

Tecnological trend	CODE	Mine Life stage	Application examples	Some topic related links
Hydrogen vehicles - green hydrogen	EMR	Extraction	nuGen™ - Mogalakwena PGM -Southafrica	https://southafrica.angloamerican.com/our-difference/futuresmart-mining/nugen https://www.azomining.com/Article.aspx?ArticleID=1705
In situ recovery	FOM	Extraction	Florence Project - Arizona (USA) Kapunda Copper ISR Project in South Australia	https://www.mining3.com/research/in-situ-recovery/ https://www.florencecopper.com/our-commitment/environment https://www.mriwa.wa.gov.au/minerals-research-advancing-western-australia/focus-areas/precision-and-low-impact-mining/
Integrated remote operating and monitoring centres (IROMCs)	MIO	All stages	Western Australia Iron Ore - BHP Rio Tinto Operation Centre - Australia	https://www.mckinsey.com/industries/metals-and-mining/our-insights/remote-operating-centers-in-mining-unlocking-their-full-potential https://www.infosys.com/engineering-services/white-papers/documents/remote-operation-center.pdf
Internet of things (IoT)	MIO	All stages	Hindustan Zinc’s Sindesar Khurd (SK) mine, India Hecla Mining Company -Casa Berardi mine, Canada Rio Tinto - Koodaideri iron ore project, Australia	https://www.analyticssteps.com/blogs/iot-mining-industry-examples-advantages-and-drawbacks
Mine backfilling	FOM	Extraction	Zinkgruvan Mine - Sweden Jiashi Copper Mine - China Sanshandao Gold Mine - China Lisheen mine - Ireland	https://www.tailings.info/storage/backfill.htm https://www.mining-technology.com/data-insights/innovation-in-extraction-technology-leading-companies-in-mine-backfilling/?cf-view
Novel geophysical methods	FOM	Exploration	Sodankylä, Kuhmo, Kylylahti, Pieksämäki Joroinen Sakatti (Finland) and Geyer (Germany) Rio Tinto Mine - Spain Cobre las Cruces Mine - Spain	https://new-exploration.tech/media/pages/media-news-events/deliverables/downloads/d5-5-a-practical-toolkit-addressed-to-mineral-exploration-and-mining-companies/3bbfe7bdaa-1657031352/d5.5-a-practical-toolkit-addressed-to-mineral-exploration-and-mining-companies-v1.0-20211027.pdf https://www.diasgeo.com/technology-innovation/full-tensor-magnetic-gradiometry-ftmg/ https://www.infactproject.eu/wp-content/uploads/2020/12/infact_d6.15_techwatch-report_final.pdf

Tecnological trend	CODE	Mine Life stage	Application examples	Some topic related links
Ore body knowledge (OBK)	MIO	All stages	RACE21 - Teck Dugald River - Australia Bathurst mining camp	https://www.teck.com/news/connect/issue/volume-30,-2020/table-of-contents/what-s-next-an-update-on-race21 https://www.csiro.au/en/work-with-us/industries/mining-resources/resourceful-magazine/issue-18 http://adimb.org.br/simexmin2022/palestras/dia30-11h20.pdf https://www.csiro.au/en/work-with-us/industries/mining-resources/Mining/VoxelNET
Ore pretreatment for grinding	MIO	Extraction	NA	
Passivation of acid mine drainage (AMD)	FOM	Extraction/Closure	Gilt Edge Mine, S.D. (EEUU) Golden Sunlight Mine, Whitehall, Montana Force Crag (UK) Rampgill (UK)	https://projects.itrcweb.org/miningwaste-guidance/to_passivation.htm
Phytomining/ Agromining	FOM	Extraction/Closure	Croesus project LTD Field trials in Albania, Spain, Greece, Zambia and Indonesia. Kinalabu Park (Malysia)	https://www.archimedesnz.com/phytomining https://energypost.eu/can-phytomining-deliver-critical-minerals-at-scale-farming-plants-that-accumulate-high-metal-concentrations/
Pulsed fast thermal neutron activation (PFTNA)	MIO	All stages	BHP Western Australia Iron Ore (BHP WAIO)	https://www.malvernpanalytical.com/en/products/technology/spectroscopy/pulsed-fast-thermal-neutron-activation
Remote sensing	MIO	Exploration/ Extraction	prototype at Newcrest's Lihir Gold Mine - Papua New Guinea Phu Kam Mine - Laos Shengli Mining Area - China	http://www.goldeneye-project.eu/
Removal of dissolved substances	FOM	Extraction/Closure	Lava Cap; Fort Hood, Killeen (EEUU) Panoche Drainage District, California (EEUU)	https://projects.itrcweb.org/miningwaste-guidance/cs33a_ft_hood.htm https://www.cmua.org/files/Water%20-%20CMUA%20BrineRemediationCMUAFinal.pdf

Tecnological trend	CODE	Mine Life stage	Application examples	Some topic related links
Renewable energy operations	EMR	Extraction	Zaldivar mine - Chile Diavik Diamond - Canada DeGrussa Mine - Australia	https://web.minerazaldivar.cl/ https://www.bhp.com/news/articles/2023/07/another-step-in-nickel-wests-decarbonisation-journey
Robotics	MIO	All stages	Kiruna - Sweden Aitik - Sweden Pilbara - Australia	https://www.globaldata.com/store/report/robotics-in-mining-theme-analysis/#:~:text=The%20two%20main%20uses%20of,rock%20cutters%20and%20inspection%20drones. https://lkab.com/en/news/spot-is-breaking-new-ground-at-lkab/ https://internationalfinance.com/how-robotics-is-changing-the-mining-industry/ https://www.ericsson.com/en/reports-and-papers/consumerlab/reports/a-case-study-on-automation-in-mining https://www.riotinto.com/en/operations/australia/pilbara
Sensor based ore sorting technology	MIO	Extraction	Bull River Mine - Canada (BC) Highland Valley - Canada Copper Mountain Antamina - Peru Australian startup NextOre. Kansanshi	https://canadiancriticalmineralsinc.com/news/canadian-critical-minerals-enters-into-ore-characterization-and-sorting-trial-with-minesense-technologies-ltd/ https://minesense.com/ https://www.metso.com/mining/solutions/in-pit-crush-and-convey-ipcc/ https://www.startus-insights.com/innovators-guide/discover-8-top-sustainable-mining-solutions/ https://im-mining.com/2021/04/14/nextores-magnetic-resonance-tech-running-first-quantums-kansanshi/
Sonic drilling	EMR	Exploration/ Extraction	Basin Project (Arizona) - Bradda Head Lithium Ltd Villeveyrac bauxite deposit (France)	https://www.mainlandmachinery.com/green-mining https://www.royaleijkelkamp.com/knowledge-hub/articles/understanding-sonic-drilling/ https://www.globalminingreview.com/exploration-development/16032023/sonic-drilling-underway-at-the-17km2-lithium-basin-project-in-arizona/
Tunnel boring machines (TBM)	FOM	Extraction	Chuquicamata mine - Chile Woodsmith mine - United Kingdom Grosvenor mine - Australia Stillwater mine - USA	https://www.komatsu.jp/en/newsroom/2022/20220708 https://www.robbinstbm.com/about/advancements/tbms-in-mining/ https://im-mining.com/2023/10/05/anglo-american-lays-out-5-mt-y-woodsmith-polyhalite-plan-ahead-of-full-design-review/